

International Journal of Modern Physics A
© World Scientific Publishing Company

A REVIEW OF CENTRAL PRODUCTION EXPERIMENTS AT THE CERN OMEGA SPECTROMETER

ANDREW KIRK

*Culham Centre for Fusion Energy, Abingdon, Oxfordshire, United Kingdom
andrew.kirk@ccfe.ac.uk*

Received
Revised

The non-Abelian nature of QCD suggests that particles that have a gluon constituent, such as glueballs or hybrids, should exist. This paper presents a study of central meson production in the fixed target experiments WA76, WA91 and WA102 at the CERN Omega spectrometer at centre-of-mass energies of $\sqrt{s} = 12.7, 23.8$ and 29 GeV. A study of the resonance production cross section as a function of \sqrt{s} shows which states are compatible with being produced by Double Pomeron Exchange (DPE). In these DPE processes, the difference in the transverse momentum between the exchange particles (dP_T) can be used to select out known $q\bar{q}$ states from non- $q\bar{q}$ candidates. The distribution of the azimuthal angle (ϕ) between the two exchange particles suggests that the Pomeron transforms like a non-conserved vector current. Finally there is evidence from an analysis of the decay modes of the scalar states observed, that the lightest scalar glueball manifests itself through the mixing with nearby $q\bar{q}$ states.

Keywords: Glueballs; Double Pomeron Exchange; WA102.

PACS numbers:12.39.Mk, 14.40.Be, 11.55.Jy, 13.85.Ni

1. Introduction

Quantum ChromoDynamics (QCD) not only describes how quarks and antiquarks interact, but also predicts that the gluons, which are the quanta of the field, will themselves interact to form mesons. If the object formed is composed entirely of valence gluons the meson is called a glueball, however if it is composed of a mixture of valence quarks, antiquarks and gluons (i.e. $q\bar{q}g$) it is called a hybrid. In addition, $q\bar{q}q\bar{q}$ states are also predicted.

The best estimate for the masses of glueballs comes from lattice gauge theory calculations¹ which show that the lightest glueball has $J^{PC} = 0^{++}$ and that

$$m(2^{++})/m(0^{++}) \approx 1.5$$

and depending on how the lattice parameters are extrapolated to the mass scale that

$$m(0^{++}) = (1500 - 1750) \text{ MeV}.$$

2 *Andrew Kirk*

The mass of the 0^{-+} glueball is predicted to be similar to that of the 2^{++} glueball whilst glueballs with other quantum numbers are predicted to be higher in mass.

The flux tube model has been used to calculate the masses of the lowest lying hybrid states and predicts² that

$$m(1^{--}, 0^{-+}, 1^{-+}, 2^{-+}) \approx 1900 \text{ MeV}.$$

Since the lightest non- $q\bar{q}$ states are predicted to have the same quantum numbers and lie in the same mass region as $q\bar{q}$ states one way to find them is to look for extra states, that is states that have quantum numbers of already completed nonets and that have masses which are sufficiently low that they are unlikely to be members of the radially excited nonets. It was hoped that these extra states would have unusual branching ratios and/or be preferentially produced in gluon rich processes such as Double Pomeron Exchange (DPE), where the Pomeron trajectory is thought to be mediated by the exchange of a virtual multi-gluon state.

The CERN fixed target experiments WA76, WA91 and WA102, which were performed at the Omega spectrometer were designed to study exclusive final states formed in the reaction

$$pp \longrightarrow p_f X^0 p_s,$$

where the subscripts f and s refer to the fastest and slowest particles, identified as protons, in the laboratory frame respectively and X^0 represents the central system. Such reactions are expected to be mediated by double exchange processes where both Pomeron and Reggeon exchange can occur.

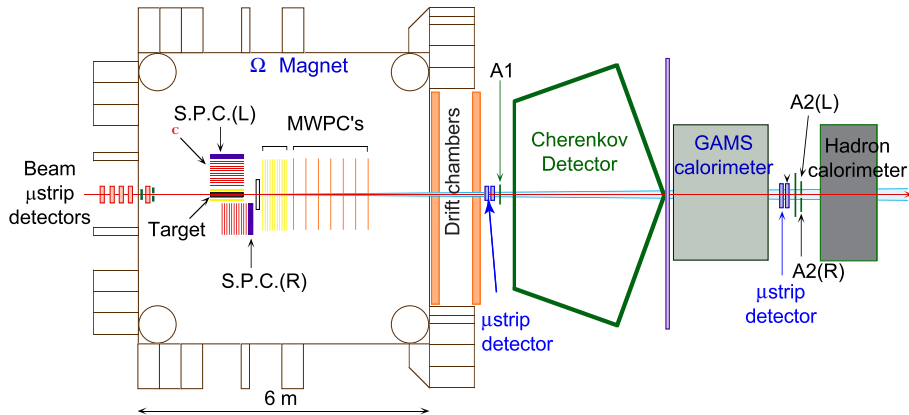


Fig. 1. Layout of the Ω spectrometer for the 1996 run of experiment WA102.

The CERN NA12/2 experiment contributed to this programme through the study of neutral decay modes of light mesons using the GAMS 4000 electromagnetic calorimeter.³ The WA76 and WA91 experiments, which were performed at the

Omega spectrometer concentrated mainly on the decay to charged particles using proton beams at 85, 300 and 450 GeV corresponding to centre-of-mass energies of $\sqrt{s} = 12.7, 23.8$ and 29 GeV. In 1995 and 1996 experiment WA102 combined the excellent charged particle reconstruction from the CERN Omega spectrometer with the neutral particle identification offered by GAMS 4000. The main results shown in this paper are from the WA102 experiment, which searched for non- $q\bar{q}$ mesons in the mass range up to 2.5 GeV. The layout of the 1996 run of WA102 is shown in fig. 1. The positively charged H1 beam in the west area was incident on a 60 cm long liquid hydrogen target. A set of ten 20 μm pitch micro-strip detectors were used to perform an accurate measurement of the incident beam's trajectory. The outgoing fast track, which had a momentum in the range 300 to 450 GeV, was measured by two sets of 4 micro-strip detectors placed 8 and 12 m downstream from the target. The Omega Multi Wire Proportional Chambers (MWPCs) and Drift Chambers were used to measure the medium momentum tracks (≈ 1 to 40 GeV) leaving the interaction region, with particle identification coming from a threshold Cerenkov counter (C1). Photon detection was provided by the GAMS-4000 lead glass calorimeter. The trigger was designed to enhance double exchange processes with respect to single exchange and elastic processes. Details of the trigger conditions, the data processing and event selection have been given in previous publications.⁴

In this paper the status of these experiments is reviewed. In section 2 the possibility that a kinematic filter exists in central production that can discriminate between gluonic and $q\bar{q}$ states is discussed while in section 3 and 4 the status of the search for the scalar and tensor glueball is presented.

2. The effect of kinematic variables on central meson production

The experiments have been performed at incident beam momenta of 85, 300 and 450 GeV, corresponding to centre-of-mass energies of $\sqrt{s} = 12.7, 23.8$ and 29 GeV. Theoretical predictions⁵ of the evolution of the different exchange mechanisms with centre of mass energy, suggest that

$$\begin{aligned}\sigma(\text{RR}) &\sim s^{-1}, \\ \sigma(\text{RP}) &\sim s^{-0.5}, \\ \sigma(\text{PP}) &\sim \text{constant},\end{aligned}$$

where RR, RP and PP refer to Reggeon-Reggeon, Reggeon-Pomeron and Pomeron-Pomeron exchange respectively. Hence it is expected that Double Pomeron Exchange (DPE) would become more significant at high energies, whereas the Reggeon-Reggeon and Reggeon-Pomeron mechanisms would decrease in importance.

The decrease of the non-DPE cross section with energy can be inferred by comparing the $\pi^+\pi^-$ mass spectrum obtained in pp interactions, under the same trigger conditions, from WA76 at $\sqrt{s} = 12.7$ GeV (fig. 2a) and from WA102 at $\sqrt{s} = 29$ GeV (fig. 2b). The $\pi^+\pi^-$ mass spectra for the two cases show that the signal-to-

4 *Andrew Kirk*

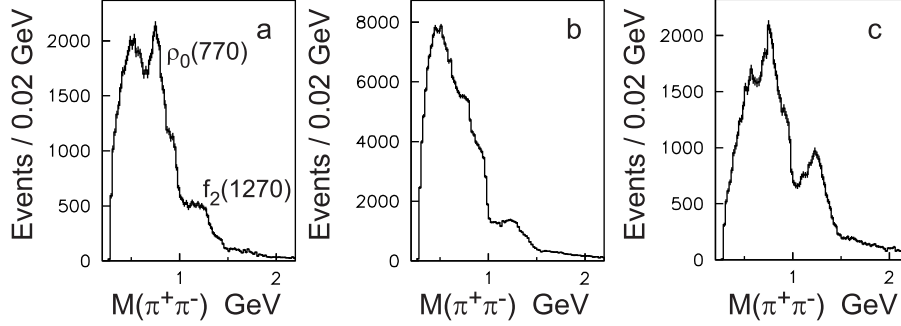


Fig. 2. The centrally produced $\pi^+\pi^-$ effective mass spectrum at \sqrt{s} = a) 12.7 GeV and b) 29 GeV using a LL trigger and c) at 29 GeV from a LR trigger.

background ratio for the $\rho^0(770)$ is much lower at high energy. The WA76 collaboration reported that the ratio of the $\rho^0(770)$ cross sections at 23.8 GeV and 12.7 GeV is 0.44 ± 0.07 .⁶ Since isospin 1 states such as the $\rho^0(770)$ cannot be produced by DPE, the decrease of the $\rho^0(770)$ signal at high \sqrt{s} is consistent with DPE becoming relatively more important with increasing energy with respect to other exchange processes. Due to the fact that there was no electromagnetic calorimeter in the WA76 experiment at \sqrt{s} of 12.7 GeV, the s dependence of only a subset of states could be determined. The states that were compatible with being produced by DPE were: η' , $f_0(980)$, $f_0(1500)$, $f_1(1285)$, $f_1(1420)$, $f_2(1270)$ and $f_2(1950)$.⁷

A comparison of the production cross-section for all the resonances observed in the WA102 experiment at $\sqrt{s} = 29.1$ GeV⁷ shows that $s\bar{s}$ states are produced much more weakly than $n\bar{n}$ states (i.e. those containing u and d quarks). For example, the cross section for the production of the $f_2(1270)$, whose production has been found to be consistent with DPE, is more than 40 times greater than the cross section of the $f_2'(1525)$. Part of this suppression could be due to the fact that there is a kinematic suppression of $M_{X^0}^{-2}$ and some could be explained by the fact that the centre of mass energy dependence of the $f_2(1270)$ allows for up to a 30 % contribution from non-DPE processes. However, a suppression of ≈ 20 still needs to be explained. Hence there could be some strong dependence on the mass of the produced quarks in DPE.

The fact that known $q\bar{q}$ states are also seen in DPE initially frustrated the hope that such experiments would prove to be a clean glueball source. However, during the experiments an additional kinematic variable was found, which was initially exposed due to a change in the trigger conditions that were implemented moving from WA76 to WA91. In the WA76 experiment in order to remove the much more frequently occurring pp elastic scattering events the trigger required that the two outgoing protons were on the same side relative to the incident beam (classified as LL) and shown pictorially in fig. 3a. In WA91 a second trigger condition was implemented, which allowed the detection of the decay of the centrally produced meson to charged

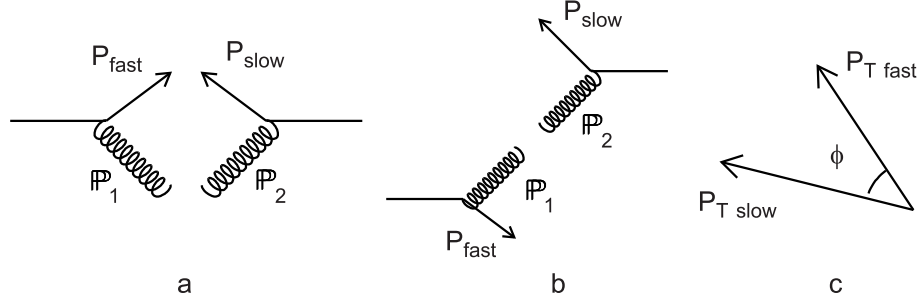


Fig. 3. Schematic diagrams in the centre of mass for a) LL and b) LR triggers. c) Definition of the azimuthal angle ϕ between the P_T vectors of the outgoing protons

particles. This allowed configurations to be recorded where the outgoing protons were on opposite sides of the beam (classified as LR), which is shown pictorially in fig. 3b. The azimuthal angle ϕ which is defined as the angle between the p_T vectors of the two outgoing protons (see fig. 3c) is small for the LL configuration and near to 180 degrees for the LR configuration. The WA91 collaboration found that there was a difference in the resonances observed for these two trigger configurations.⁸ Fig. 2b and c compares the $\pi^+\pi^-$ mass spectrum obtained with the LL and LR trigger configuration from WA102 at $\sqrt{s} = 29$ GeV. In the LR configuration, the $\rho^0(770)$ and $f_2(1270)$, known $q\bar{q}$ states are very prominent. The SFM collaboration at the ISR had also observed that the directions taken by the outgoing fastest and slowest particles were correlated with the production of the $f_2(1270)$,⁹ however, in that case they concluded that the observation may suggest that the $f_2(1270)$ may have a large glue content. In the case of WA91, since the $\rho^0(770)$ and $f_2(1270)$ have a similar dependence the conclusion drawn was that the configuration of the outgoing protons may provide a way of distinguishing between $q\bar{q}$ and non- $q\bar{q}$ states.

In fact, the WA91 collaboration⁸ showed that there were a wide variety of resonances that favoured production when the angle between the outgoing slow and fast protons was near to 0 degrees compared to when the angle was near to 180 degrees. In order to try to explain this effect in terms of a physical model, Close and Kirk¹⁰ proposed that the data be analysed in terms of the parameter dP_T , which is the difference in transverse momentum between the particles exchanged from the fast and slow vertices.

The WA102 collaboration presented studies of how different resonances were produced as a function of the parameter dP_T (see⁷ and references therein). The fraction of each resonance was calculated for $dP_T \leq 0.2$ GeV and $dP_T \geq 0.5$ GeV and the ratio of the production at small dP_T to large dP_T was found to be a useful discriminant.⁷ It was found that all the undisputed $q\bar{q}$ states (for example, η , η' , $f_1(1285)$, $f_1(1420)$, $f_2(1270)$ and $f_2(1525)$) which can be produced in DPE, namely those with positive G parity and $I = 0$, have a very small value for this ratio (≤ 0.1). However, the interesting states, which could have a non- $q\bar{q}$ or gluonic component

6 *Andrew Kirk*

have a large value for this ratio,⁷ for example $f_0(980)$, $f_0(1500)$, $f_0(1710)$, $f_2(1910)$ and $f_2(1950)$.

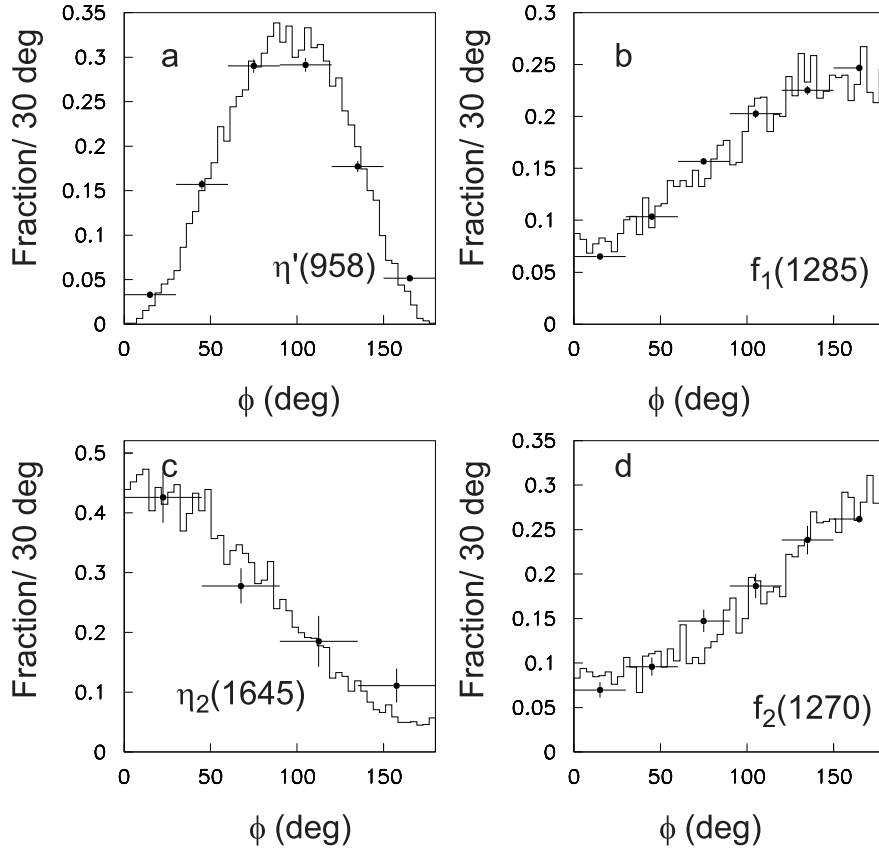


Fig. 4. The ϕ dependence for undisputed $q\bar{q}$ states a) η' , b) $f_1(1285)$, c) $\eta_2(1645)$ and d) $f_2(1270)$ for the data (dots) and the model (histogram).

In addition to the dP_T dependencies, an interesting effect was observed in the azimuthal angle ϕ which is defined as the angle between the p_T vectors of the two outgoing protons (see 3c). Previously it had been assumed that the Pomeron, which is said to have “vacuum quantum numbers”, transforms as a scalar and hence that the ϕ distribution would be flat for resonances produced by DPE. Fig. 4 shows the ϕ dependence for the production of undisputed $q\bar{q}$ states with a range of spin quantum numbers, J^{PC} . The observed ϕ dependencies are clearly not flat and considerable variation is observed among the resonances produced. For the $q\bar{q}$ mesons that can be produced by DPE the ϕ distributions maximise around 90° for resonances with $J^{PC} = 0^{-+}$, at 180° for those with $J^{PC} = 1^{++}$ and at 0° for those with $J^{PC} = 2^{-+}$.

Several theoretical papers have been published on these effects.^{11,12} All agree that the exchanged particle must have $J > 0$ and that $J = 1$ is the simplest explanation for the observed ϕ distributions. Close and Schuler¹² have calculated the ϕ dependencies for the production of resonances with different J^{PC} for the case where the exchanged particle is a Pomeron that transforms like a non-conserved vector current. In order to gain insight into the nature of the particles exchanged in central pp interactions Close, Kirk and Schuler¹³ compared the predictions of this model with the data for resonances with different J^{PC} observed in the WA102 experiment. They found that for the production of $J^{PC} = 0^{-+}$ mesons they could predict the ϕ dependence as well as the observed vanishing cross section as $t \rightarrow 0$ absolutely. Superimposed on fig. 4a is the prediction of this model. The model was also able to predict the ϕ dependence for the $J^{PC} = 1^{++}$ and 2^{-+} mesons (fig. 4b and c).¹³ In the 0^{++} and 2^{++} sector the ϕ distributions can be fitted with one parameter (μ^2), where the sign of this parameter determines if the ϕ distribution is peaked at 0° or 180° . For example, fig. 4d shows the ϕ dependence for the $f_2(1270)$ which can be well described with $\mu^2 = -0.4 \text{ GeV}^2$. Understanding the dynamical origin of this sign then became a central issue in the quest to distinguish $q\bar{q}$ states from glueballs or other exotic states and this will be discussed in the following sections.

One of the first applications of these kinematic filters was to the axial vector nonet. At the start of the WA102 experiment the $f_1(1420)$, which was prominently observed in central production, was thought to be a non- $q\bar{q}$ candidate (see¹⁴ and references therein). There appeared to be three candidates for the $I=0$ members of the $J^{PC} = 1^{++}$ nonet: $f_1(1285)$, $f_1(1420)$ and $f_1(1510)$. However, the application of these kinematic selections showed that the $f_1(1285)$ and $f_1(1420)$ have the same behaviour; namely consistent with the $f_1(1420)$ being the partner to the $f_1(1285)$ in the 3P_1 nonet of axial mesons. The conclusion reached from the analysis presented in ref.¹⁴ was that without confirmation of the existence of the $f_1(1510)$ the isoscalar members of the $J^{PC} = 1^{++}$ nonet should be considered to be the $f_1(1285)$ and $f_1(1420)$ with a singlet-octet mixing angle of approximately 50° .

3. The search for the scalar glueball

In the 1990s the search for non- $q\bar{q}$ states became possible due to the advent of high statistics experiments. To identify a scalar non- $q\bar{q}$ state the first question to ask is how many 0^{++} states are there in the 1-2 GeV mass region. The problem was that in the scalar sector there appeared to be a multitude of states, with different experiments claiming new scalar states that had effectively no overlap in their mass and width. It quickly became apparent that in order to compare results from different experiments a unified and unitarised method of analysis was required.

A good example of why such an approach is required can be seen by looking at what was being reported in the 1.5 GeV mass region in 1994. In addition to the $f_0(1370)$ and $f_0(1710)$, several experiments had observed apparently different scalar states. The GAMS collaboration observed a $G(1590)$ decaying to $\eta\eta$ and $\eta\eta'$.³

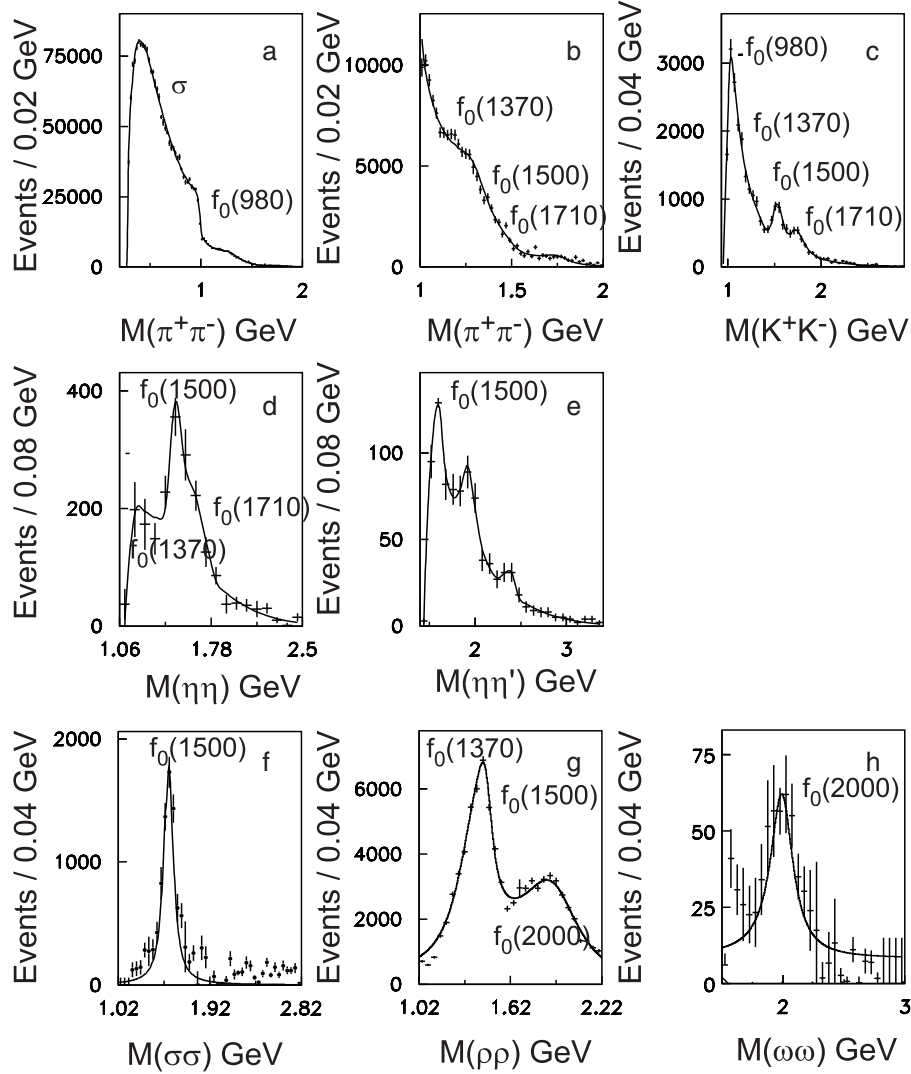


Fig. 5. The S-wave contributions to the a),b) $\pi^+\pi^-$, c) K^+K^- , d) $\eta\eta$, f) $\sigma\sigma$, g) $\rho\rho$ and h) $\omega\omega$ mass spectra and e) the total $\eta\eta'$ mass spectra. The location of the $J^{PC} = 0^{++}$ states identified are indicated.

Experiments WA76 and WA91 observed a narrow state ($\Gamma \approx 50$ MeV) called the X(1450) in the centrally produced $\pi^+\pi^-\pi^+\pi^-$ channel.¹⁵ While the Crystal Barrel experiment observed the $f_0(1500)$ in several final states in $p\bar{p}$ annihilations.¹⁶ Therefore there appeared to be three new scalar states around 1.5 GeV, each observed in different experiments. However under closer examination it became apparent that all three states were in fact the same and it was only the analysis techniques that made them appear different. The difference in mass between the states observed by

the Crystal Barrel collaboration and the GAMS collaboration could be reconciled if they both used the same Breit-Wigner parameterisation. To reconcile the data from WA91 required invoking the idea that there could be an interference between coherently produced states. A previously known example of this coherent interference is the observation of the $f_0(980)$ in central production.¹⁷ In the KK channel the $f_0(980)$ appears as a peak near threshold (see for example fig. 5c), whereas in the $\pi\pi$ channel, due to interference with the low mass s-wave continuum or σ , it often appears as a dip in the mass spectrum (see fig. 5a).¹⁷

In a similar way the WA91 collaboration showed that the X(1450) could be explained as being due to the coherent interference of the $f_0(1370)$ and the $f_0(1500)$.¹⁸ Fig. 5 shows all the $J^{PC} = 0^{++}$ states observed by the WA102 collaboration. These states were observed in the $\pi\pi$ ^{19, 20}, KK ^{20, 21}, $\eta\eta$,²² $\eta\eta'$,²³ 4π ²⁴ and $\omega\omega$ ²⁵ final states. In addition to the low mass $\pi\pi$ continuum or σ ($f_0(500)$) these are $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$ and $f_0(2000)$.

The fact that there are three clearly established states, the $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$, in a region where the standard nonet structure would only require two and that this is the mass region expected for the scalar glueball, meant that it was possible that one of these states could be the scalar glueball. However, none of them had the decay modes characteristic of a glueball state and so it was postulated that the observed states are in fact a result of the mixing of the glueball with the nearby $q\bar{q}$ states with the same J^{PC} (see²⁶ and references therein). Such a mixing would lead to three isoscalar states and the relative gg to $q\bar{q}$ content of these states would lead to a predictable pattern of decay branching ratios.^{27–29}

The observation of these states in a wide range of decay modes meant that, for the first time, a complete data set of the two-body decays of these states was available and this was used to extract their quark content. The WA102 data, presented in fig. 5, produced the following relative decay rates:²⁶

$$\begin{aligned} \pi\pi : K\bar{K} : \eta\eta : \eta\eta' : 4\pi \\ f_0(1370): 1 : 0.46 \pm 0.19 : 0.16 \pm 0.07 : 0.0 : 34.0^{+22}_{-9} \\ f_0(1500): 1 : 0.33 \pm 0.07 : 0.18 \pm 0.03 : 0.096 \pm 0.026 : 1.36 \pm 0.15 \\ f_0(1710): 1 : 5.0 \pm 0.7 : 2.4 \pm 0.6 : < 0.18 \text{ (90 \% CL)} : < 5.4 \text{ (90 \% CL)} \end{aligned}$$

These data were used as input to a fit to investigate the glueball-quarkonia content of the $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$. In the $|G\rangle = |gg\rangle$, $|S\rangle = |s\bar{s}\rangle$, $|N\rangle = |u\bar{u} + d\bar{d}\rangle/\sqrt{2}$ basis, the physical states $|f_0(1710)\rangle$, $|f_0(1500)\rangle$ and $|f_0(1370)\rangle$ were found to be²⁶

$$\begin{aligned} |f_0(1710)\rangle &= 0.42|G\rangle + 0.89|S\rangle + 0.17|N\rangle, \\ |f_0(1500)\rangle &= -0.61|G\rangle + 0.37|S\rangle - 0.69|N\rangle, \\ |f_0(1370)\rangle &= 0.65|G\rangle - 0.15|S\rangle - 0.73|N\rangle. \end{aligned}$$

The transformation matrix obtained, although not imposed, is close to being unitary indicating the robustness of the solution.²⁶ The solution shows that the

glue content is shared between the three states, it is in phase with the $n\bar{n}$ content in the $f_0(1500)$ and $f_0(1710)$ and out of phase in the $f_0(1370)$. The $s\bar{s}$ content is dominantly in the $f_0(1710)$. This solution was consistent with the production of these states in $\gamma\gamma$ collisions, $p\bar{p}$ annihilations and in radiative J/ψ decays.²⁶ For central production, as was discussed in section 2, the cross sections of well established quarkonia in WA102 suggest that the production of $s\bar{s}$ is strongly suppressed relative to $n\bar{n}$. The relative cross sections for the three states are $pp \rightarrow pp + (f_0(1710) : f_0(1500) : f_0(1370)) \sim 0.14 : 1.7 : 1$. This would be natural if the production were via the $n\bar{n}$ and gg components of DPE. There is an important qualitative difference for these three states in the distribution of the azimuthal angle ϕ between the p_T vectors of the two outgoing protons (see fig. 6). The $f_0(1710)$ and $f_0(1500)$ peak as $\phi \rightarrow 0$ whereas the $f_0(1370)$ is more peaked as $\phi \rightarrow 180^\circ$. While it is possible to explain these observations by postulating that the gg and $n\bar{n}$ components are produced coherently (positive μ^2) as $\phi \rightarrow 0$ but are out of phase (negative μ^2) as $\phi \rightarrow 180^\circ$,²⁶ no such explanation for the observed production of these states as a function of dP_T has been attempted.

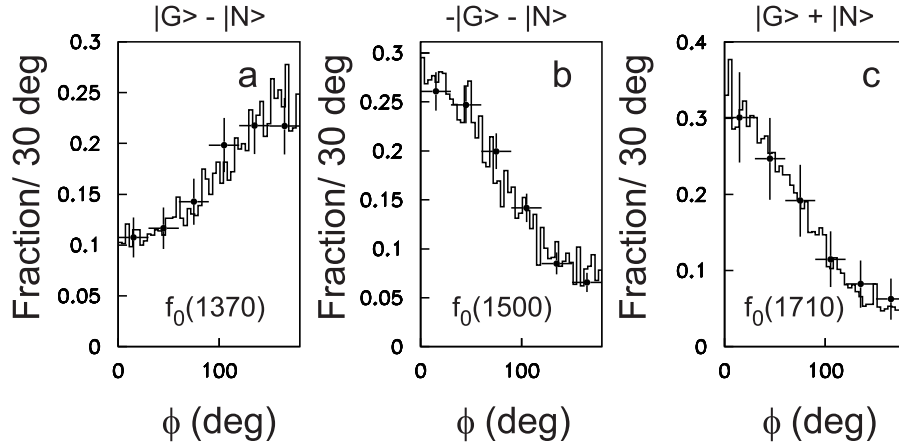


Fig. 6. The ϕ dependence for a) $f_0(1370)$, b) $f_0(1500)$ and c) $f_0(1710)$ for the data (dots) and the model (histogram).

4. The search for the tensor glueball

The tensor sector is much less explored and the level of cross machine analysis is much lower than in the scalar sector. However, interesting candidates do exist. The WA76 collaboration reported the observation of a previously unobserved meson with a mass of 1950 MeV and width of 450 MeV in the $\pi^+\pi^-\pi^+\pi^-$ final state at a incident beam momentum of 300 GeV.³⁰ A spin parity analysis performed by the WA102 collaboration showed that it has $I^G(J^{PC}) = 0^+(2^{++})$, with $J_Z = 0$

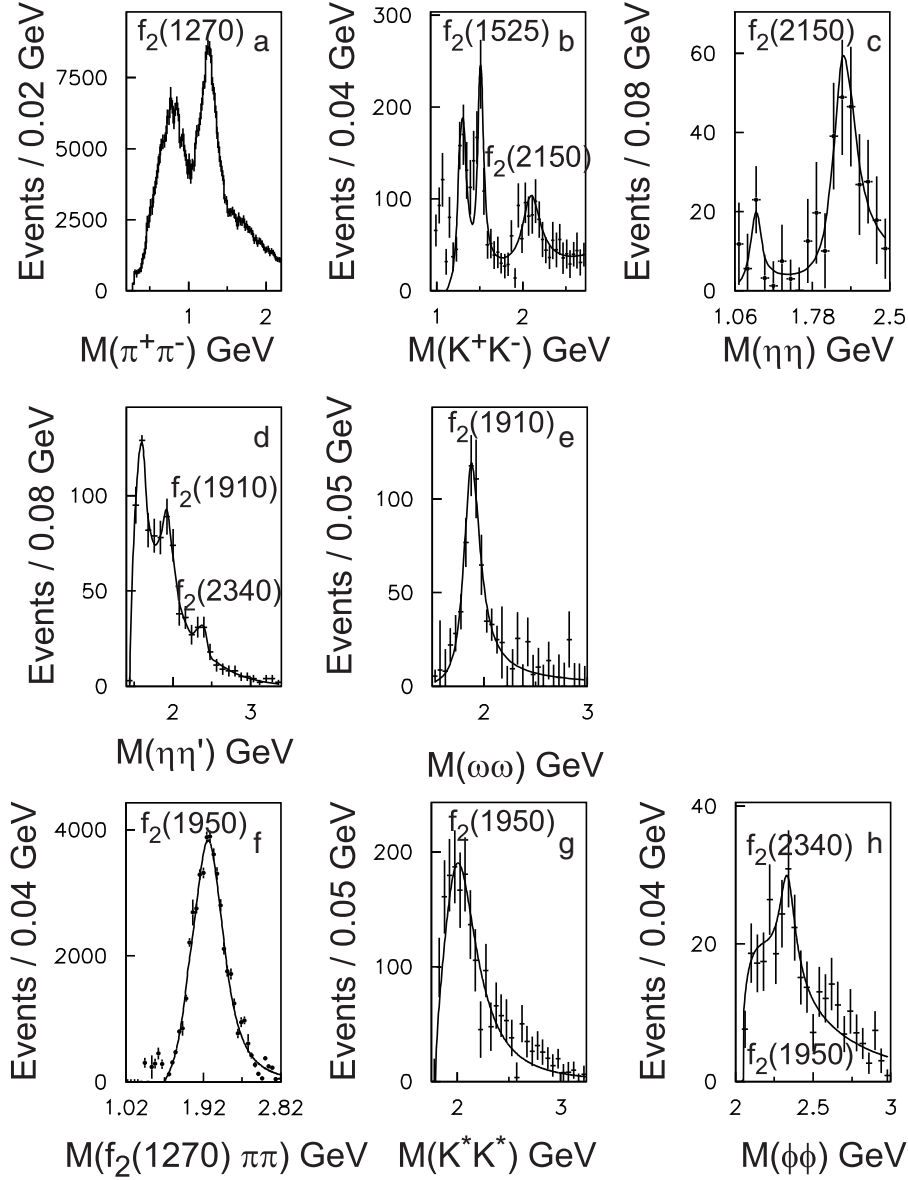


Fig. 7. The D-wave contributions to the a) $\pi^+\pi^-$, b) K^+K^- , c) $\eta\eta$, e) $\omega\omega$, f) $f_2(1270)\pi\pi$, g) K^*K^* and h) $\phi\phi$ mass spectra and d) the total $\eta\eta'$ mass spectra. The location of the $J^{PC} = 2^{++}$ states identified are indicated.

and decays dominantly to $f_2(1270)\pi\pi$ with smaller decays to K^*K^* and $\phi\phi$.²⁴ The observation of this state in DPE combined with the fact that the mass coincides with that expected for a state with $J=2$ on the Pomeron trajectory³¹ led to speculation that this may be the tensor glueball. However, this was not the only tensor state

observed in this mass region. Figure 7 shows all the states with $I^G(J^{PC}) = 0^+(2^{++})$ observed by WA102. The isoscalar ground state nonet members, the $f_2(1270)$ and $f_2(1525)$, are clearly observed in the $\pi^+\pi^-$ and K^+K^- D-wave respectively, both are produced with $J_Z = 0$. A state called the $f_2(2150)$ is observed decaying to K^+K^- and $\eta\eta$. Another state in the 1.9 GeV region is observed in the $\eta\eta'$ and $\omega\omega$ final states. The reason that this state is thought to be distinct from the $f_2(1950)$ is due to the fact that it is produced exclusively with spin projection $J_Z = 2$; the only state observed in WA102 with $J_Z \neq 0$. It is also narrower with a width of 200 MeV.

As in the scalar sector there appears to be three states where only two would be expected and as can be seen from fig. 8 the ϕ distributions show that the $f_2(1910)$ and $f_2(1950)$ peak at 0° , while the $f_2(2150)$ peaks near to 180° . Unfortunately there is not enough information on their decay modes to try to extract their relative glue content. However, like the $f_0(1500)$ and $f_0(1710)$ in the scalar sector the $f_2(1910)$ and $f_2(1950)$ are produced predominantly at small dP_T . While the $f_2(1950)$ is accepted as an established state and appears in the summary tables of the Particle Data Group book³² the $f_2(1910)$ is not included. To resolve the tensor glueball further studies are required.

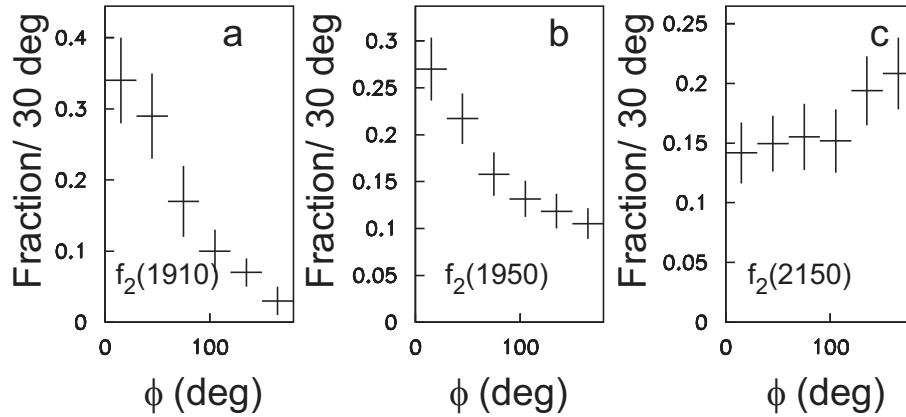


Fig. 8. The ϕ dependence for a) $f_2(1910)$, b) $f_2(1950)$ and c) $f_2(2150)$.

5. Conclusions

Quantum ChromoDynamics (QCD) not only describes how quarks and antiquarks interact to form the standard $q\bar{q}$ mesons but also predicts the existence of glueballs, hybrids and four-quark states. These states should be produced in Double Pomeron Exchange. Fixed target experiments at the CERN Omega spectrometer have studied centrally produced mesons at centre-of-mass energies of $\sqrt{s} = 12.7, 23.8$ and 29 GeV. This range of energies has allowed the relative strength of the DPE process to be

investigated. Cuts on the dP_T variable select out known $q\bar{q}$ states from non- $q\bar{q}$ or glueball candidates. Why this works is still to be understood. The azimuthal angle ϕ has given information on the nature of the Pomeron, which is consistent with it transforming like a non-conserved vector current. Based on the decay rates of the scalar states observed by WA102 and on the hypothesis that the scalar glueball mixes with the nearby $q\bar{q}$ nonet states, the flavour content of the $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ has been determined. The solution found is also compatible with the relative production strengths of the $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ in $\gamma\gamma$ collisions, $p\bar{p}$ annihilations and J/ψ radiative decays. Tensor candidates exist but further studies are required to resolve this sector.

References

1. G. Bali et al. (UKQCD), *Phys. Lett.* **B309**, 378 (1993);
D. Weingarten, hep-lat/9608070;
J. Sexton et al., *Phys. Rev. Lett.* **75**, 4563 (1995);
F.E. Close and M.J. Teper, "On the lightest Scalar Glueball" Rutherford Appleton Laboratory report no. RAL-96-040; Oxford University report no. OUTP-96-35P
2. N. Isgur, AIP. Conf. Proc. 185, Particles and Fields 36, Glueballs, hybrids and exotic hadrons, (1988) 3
3. F. Binon *et al.*, *Nuovo Cimento* **A78**, 313 (1983);
D. Alde *et al.*, *Phys. Lett.* **B201**, 160 (1988).
4. T.A. Armstrong *et al.*, *Nucl. Instr. and Methods* **A274**, 165 (1989);
F. Antinori *et al.*, *Il Nuovo Cimento* **A107**, 1857 (1994).
5. S.N. Ganguli and D.P. Roy, *Phys. Rep.* **67**, 203 (1980).
6. T.A. Armstrong *et al.*, *Zeit. Phys. C* **51**, 351 (1991).
7. A. Kirk *Phys. Lett.* **B489**, 24 (2000).
8. D. Barberis *et al.*, *Phys. Lett.* **B388**, 853 (1996).
9. A. Breakstone *et al.*, *Zeit. Phys. C* **48**, 569 (1990).
10. F.E. Close and A. Kirk, *Phys. Lett.* **B397**, 333 (1997).
11. F.E. Close, *Phys. Lett.* **B419**, 387 (1998);
P. Castoldi, R. Escribano and J.-M. Frere, *Phys. Lett.* **B425**, 359 (1998);
N. I. Kochelev, hep-ph/9902203;
N.I. Kochelev, T. Morii and A.V. Vinnikov, *Phys. Lett.* **B457**, 202 (1999);
F.E. Close and G. Schuler, *Phys. Lett.* **B458**, 127 (1999).
12. F.E. Close and G. Schuler, *Phys. Lett.* **B464**, 279 (1999).
13. F.E. Close, A. Kirk and G. Schuler, *Phys. Lett.* **B477**, 13 (2000).
14. F.E. Close and A. Kirk, *Z. Phys. C* **76**, 469 (1997).
15. S. Abatzis *et al.*, *Phys. Lett.* **B324**, 509 (1994).
16. V. V. Anisovitch *et al.*, *Phys. Lett.* **B323**, 233 (1994);
C. Amsler *et al.*, *Phys. Lett.* **B342**, 433 (1995);
C. Amsler *et al.*, *Phys. Lett.* **B291**, 347 (1992);
C. Amsler *et al.*, *Phys. Lett.* **B340**, 259 (1994).
17. T. Akesson *et al.*, *Nucl. Phys. Lett.* **B264**, 154 (1986);
K.L. Au, D. Morgan and M.R. Pennington, *Phys. Rev. D* **35**, 1633 (1987).
18. F. Antinori *et al.*, *Phys. Lett.* **B353**, 589 (1995).
19. D. Barberis *et al.*, *Phys. Lett.* **B453**, 316 (1999);
D. Barberis *et al.*, *Phys. Lett.* **B453**, 325 (1999).
20. D. Barberis *et al.*, *Phys. Lett.* **B462**, 462 (1999).

21. D. Barberis *et al.*, *Phys. Lett.* **B453**, 305 (1999).
22. D. Barberis *et al.*, *Phys. Lett.* **B479**, 59 (2000).
23. D. Barberis *et al.*, *Phys. Lett.* **B471**, 435 (2000).
24. D. Barberis *et al.*, *Phys. Lett.* **B474**, 423 (2000).
25. D. Barberis *et al.*, *Phys. Lett.* **B484**, 198 (2000).
26. F.E. Close and A. Kirk, *Phys. Lett.* **B483**, 345 (2000).
27. C. Amsler and F.E. Close, *Phys. Lett.* **B353**, 385 (1995).
28. F.E. Close, *Rep. Prog. Phys.* **51**, 833 (1988).
29. F.E. Close, G. Farrar and Z.P. Li, *Phys.Rev.* **D55**, 5749 (1997).
30. T.A. Armstrong *et al.*, *Phys. Lett.* **B228**, 536 (1989).
31. S. Donnachie *et al.*, *Pomeron Physics and QCD*, Cambridge University Press 2003
32. J. Beringer *et al.*, *Phys. Rev.* **D86**, 010001 (2012).